Paste 2026 – AB Fourie, M Horta, M Oliveira & S Wilson (eds)

doi:10.36487/ACG_repo/2655_22

Hydrogeological monitoring of the Cerro do Lobo tailings storage facility using the geophysical method for sustainable groundwater flow detection and tailings management

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Abstract

The Neves-Corvo mine, located in Beja district (Lower Alentejo, Portugal), is a polymetallic mine primarily producing copper and zinc. In 1988, the Cerro del Lobo tailings and waste rock storage facility was constructed following the best available practices at the time. The facility is unlined at its base and rests directly on a bedrock of schists and greywackes.

A major environmental concern is the potential migration of conductive groundwater beyond the facility's perimeter. To assess this, the geophysical method of electrical resistivity tomography (ERT) has been applied in recent years along profiles around the Cerro do Lobo and in more distant areas where subsurface water flow is present. ERT involves injecting electrical current through a pair of electrodes and measuring the response with another pair, producing a subsurface resistivity pseudo-section. Combined with geological knowledge, this method allows the identification of subsurface structure and composition, detection of possible groundwater flow paths, and identification of low-resistivity zones, guiding the placement of additional monitoring points.

Groundwater circulation is typically associated with tectonic structures (faults and thrusts). While infiltration is not evident at the base of the facility, it is detectable in the surrounding areas, gradually decreasing with distance. Chemical analyses from piezometers, installed based on geophysical results, have validated the method's effectiveness. All geophysical information has been incorporated into hydrogeological studies, providing direct support for the mine closure plan.

This study demonstrates that ERT is a powerful and practical tool for groundwater monitoring in tailings storage facilities, enabling improved understanding of subsurface flow and contributing to sustainable tailings management and environmental protection.

Keywords: *tailings storage facility, geophysics, groundwater, subsurface resistivity, tectonic structures, environmental protection*

1 Introduction

Modern society heavily depends on mineral resources, making mining a fundamental activity for technological and economic development. Nevertheless, the industry carries a historical legacy of severe environmental impacts, often linked to inadequate waste management and the absence of proactive

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environmental controls. In Portugal, this legacy is clearly visible in numerous abandoned mines across the Iberian Pyrite Belt (IPB), where acid mine drainage and the contamination of soils and water resources from tailings and waste rock remain major environmental liabilities (Mourinha et al. 2022; Oliveira et al. 2022).

This background has driven a paradigm shift in mining towards proactive and sustainable practices. It is now widely recognised that rigorous geo-environmental monitoring is essential throughout the entire mine lifecycle – from operation to closure and post-closure – to anticipate, mitigate, and remediate potential impacts. In this framework, hydrogeological and geophysical approaches have gained increasing importance as complementary tools for monitoring and management (Rey et al. 2020).

The Neves-Corvo mine, located in the Portuguese portion of the IPB (Lower Alentejo, Beja district), is a high-grade underground polymetallic operation primarily producing copper and zinc, with additional lead and tin (Relvas et al. 2002). Since the late 1980s, the Cerro do Lobo tailings storage facility (TSF) has been the main repository for tailings and waste rock generated by the operation. The facility was originally designed for subaqueous deposition of slurry tailings which was phased out in 2010 (Abreu 2025). Since 2011, it has operated under a subaerial thickened tailings stacking system, co-disposing potentially acid-generating (PAG) waste rock. Currently, the TSF has accumulated approximately 38 Mm^3 of slurry tailings and waste rock. Mineralogically, the deposits are rich in sulphides (pyrite, sphalerite, chalcopyrite, arsenopyrite) and gangue phases (quartz, phyllosilicates, carbonates), creating conditions for potential acid generation and metal release if exposed to water and oxygen.

A major environmental concern at Cerro do Lobo is the possible migration of conductive groundwater beyond the facility's perimeter, especially through tectonic structures (faults and thrusts) and fractures in the underlying schists and greywackes. Such migration could result in the spread of contaminated leachate, with implications for both groundwater resources and surface water bodies. Therefore, understanding groundwater flow paths in and around the TSF is a critical requirement for sustainable mine water management and closure planning.

To address this challenge, non-invasive geophysical methods, particularly electrical resistivity tomography (ERT), offer valuable capabilities. By imaging subsurface resistivity distributions, ERT enables the detection of the phreatic level, distinguishing the unsaturated from the saturated zone, preferential groundwater flow pathways along fractures/faults and weathered zones, and low-resistivity anomalies potentially associated with seepage or contamination (Martínez-Moreno et al. 2017). When integrated with hydrogeological and geochemical information, ERT becomes a powerful tool for designing monitoring networks, guiding the placement of piezometers, and supporting mitigation strategies (Martos-Rosillo et al. 2019).

This paper presents the application of ERT around the Cerro do Lobo TSF at Neves-Corvo. The study illustrates how geophysics, combined with hydrogeological knowledge, provides actionable insights into groundwater circulation and supports sustainable tailings management. Ultimately, this work contributes to advancing best practices in environmental monitoring, with direct relevance to mine closure and long-term environmental protection.

2 Site characterisation: the Neves-Corvo mine and the Cerro do Lobo tailings storage facility

2.1 Geological setting

The Neves-Corvo mine is located in the western sector of the IPB, a Variscan-age metallogenic province extending ~250 km across southern Portugal and southwestern Spain (Sáez et al. 2024; Batista 2020). The IPB is globally recognised as one of the largest and most significant provinces of volcanogenic massive sulphide deposits, including world-class districts such as Rio Tinto, Aljustrel and São Domingos.

At Neves-Corvo, the local stratigraphy consists of a Paleozoic sequence where the Phyllite-Quartzite Group forms the basal unit. This is overlain by the volcanic–sedimentary complex, which hosts the polymetallic ore bodies. Mineralisation is associated with volcanic and volcaniclastic units, strongly deformed and disrupted by tectonic processes. Structurally, the region is characterised by folding, faulting and fracturing, which control not only the geometry of the orebodies but also the hydrogeological behaviour of the rock mass. The dominant lithologies in the surroundings of the Cerro do Lobo TSF are schists and greywackes, which, although of generally low primary permeability, contain numerous fracture zones that act as preferential conduits for groundwater flow.

The Neves-Corvo mine was discovered in 1977 and went into full-scale production in 1988, with initial focus on copper extraction (Oliveira et al. 2004). Over time, its product mix expanded to include significant zinc, lead and tin concentrates. To date, Neves-Corvo has processed several million tonnes (Mt) per year of ores, with production of copper and zinc in the order of hundreds of thousands of tonnes annually. Ore reserves have been estimated at roughly 27.7 Mt of copper-bearing material averaging ~3.0 % copper (Cu), and 23.1 Mt of zinc ore averaging ~7.3 % zinc (Zn). The operation is managed by Somincor (Sociedade Mineira de Neves-Corvo), formerly part of Lundin Mining and more recently acquired in 2025 by Boliden. The mine's scale, longevity, and metallurgical complexity make it a cornerstone of IPB mining and a prime case study for environmental and tailings management in polymetallic operations.

2.2 Hydrogeological context

The hydrogeological system at Neves-Corvo is conceptualised into 3 main units: the superficial system, the intermediate system, and the deep mining system (Fernández-Rubio and Fernández Lorca 1985; Fernández-Rubio et al. 2015; LNEG 2019; Somincor 2024):

- Superficial system (0–50 m depth): this unit corresponds to the weathered and decompressed zone of the bedrock, characterised by fracturing and relatively high permeability near the surface. It is an unconfined to semi-confined aquifer, recharged directly by rainfall and the catchment of the Ribeira de Oeiras, the main river in the area. Groundwater in this system is cold and calcium-bicarbonate (Ca-HCO_3) dominated, and permeability decreases with depth. the superficial system is influenced by the mine's dewatering cone, which affects water levels even during periods of high recharge.
- Intermediate system (50 m depth to the top of the ore bodies): this unit behaves as a low-permeability aquitard or aquifuge. Water movement occurs almost exclusively through subvertical faults and fractures, which serve as preferential flow paths with locally high hydraulic conductivity. Originally, natural circulation in this system was slow and limited, but mining activity has modified its behaviour. Today, waters show mixed hydrochemical characteristics and temperatures between 25–29˚C, reflecting interaction with both shallow and deep systems.
- Deep mining system (ore bodies and surrounding wall rocks, >150 m depth, up to >800 m in mining zones): this system is a confined aquifer with a high storage coefficient, primarily due to intense fracturing, micro-fracturing, and the brittle behaviour of the ore zones. Groundwater in this system is pristine, sodium-chloride (Na-Cl) type, under high pressure and elevated temperatures (>46˚C). Mine dewatering has created a cone of depression, connecting the 3 hydrogeological systems through faults, which allows shallow, cold bicarbonate waters to reach deeper zones and generates mixed hydrochemical signatures in intermediate areas.

From a hydrogeochemical perspective, 4 main water facies are recognised in the Neves-Corvo area (LNEG 2019):

- calcium-sulphate (Ca-SO_4): influenced by mine drainage
- Ca-HCO_3: shallow groundwater
- sodium-bicarbonate (Na-HCO_3): deep groundwater affected by ion exchange and mixing
- Na-Cl: pristine deep groundwater.

The hydrogeological configuration emphasises that groundwater flow is structurally controlled, with faults and fracture networks dominating connectivity between the systems. This structural control is critical for understanding potential migration of seepage from the Cerro do Lobo TSF and for the design of monitoring and mitigation measures.

2.3 The Cerro do Lobo tailings storage facility

The Cerro do Lobo TSF, also known as Instalações de Rejeitados do Cerro do Lobo (IRCL) , was constructed in 1988 to store tailings and waste rock from the Neves-Corvo processing plants (Abreu 2025). Initially, the facility operated using subaqueous deposition of tailings slurry to minimise oxidation and metal mobilisation. In 2010, operations shifted to a subaerial thickened tailings stacking system, which included the co-disposal of PAG waste rock. By 2019, the TSF had accumulated approximately 47 Mt of residues (~30 Mt of tailings and ~7.3 Mt of waste rock), establishing it as one of the largest tailings facilities in the IPB (Lopes et al. 2015).

A critical design feature of Cerro do Lobo is the absence of a synthetic liner at its base, which places the tailings in direct contact with the underlying schists and greywackes (Lundin Mining 2022, 2024). Although these lithologies have low primary permeability, the presence of extensive fractures, joints, and shear zones creates preferential pathways for groundwater flow. Consequently, seepage through structurally controlled zones represents a potential hydrogeological risk, particularly where these features connect the facility with the surrounding groundwater systems.

The facility is built on gently sloping terrain, a feature that, combined with climatic recharge and mine-induced dewatering, influences the direction and velocity of infiltrating water. Monitoring and hydrogeological modelling indicate that seepage from the TSF can enter the shallow superficial system (0–50 m) and, via fractures, potentially migrate deeper into the intermediate and deep mining systems (>150 m).

The primary risk to water quality stems from the tailings' mineralogical composition, which is dominated by sulphides such as pyrite, chalcopyrite, sphalerite, and arsenopyrite. Upon oxidation, these minerals can generate acidic and metal-rich seepage. To mitigate this risk, a combination of geophysical and hydrogeological monitoring has been implemented. ERT profiles are used to guide the placement of piezometers, enabling early detection of groundwater flow paths and the identification of low-resistivity zones corresponding to potential seepage. Furthermore, chemical analysis of water samples allows for a clear differentiation between natural groundwater facies ($Ca\text{-}HCO_3$, $Na\text{-}HCO_3$, Na-Cl) and tailings-influenced waters ($Ca\text{-}SO_4$).

The Cerro do Lobo TSF exemplifies the challenges of managing a large, unlined tailings facility on fractured, structurally complex bedrock. Its design, mineralogical characteristics, and hydrogeological context require an integrated monitoring strategy – combining structural mapping, geophysical imaging, and hydrogeochemical analysis – to ensure sustainable tailings management and environmental protection.

3 Electrical resistivity tomography method

Geophysics is the branch of science that studies the Earth's subsurface from the surface without causing harm to humans or the environment. In simple terms, it allows us to obtain an image of the underground, much like taking a radiograph of the terrain, without drilling (Everett 2013). Among the different geophysical methods – gravity, magnetics, seismic, and electrical – the electrical and, when possible, electromagnetic methods are the most suitable for assessing environmental impacts related to mining activities.

Direct current (DC) electrical methods involve injecting a known electric current into the ground and measuring the response. Steel rods of about 20 cm, called electrodes, are used to form a closed electrical circuit. Current is injected through one pair of electrodes, while another nearby pair measures the resulting potential difference with a millivoltmeter. This allows us to infer the subsurface resistivity, which is sensitive to the presence of natural or conductive waters, minerals and other subsurface materials (Martínez-Moreno et al. 2013).

Within ERT, different electrode configurations can be used, each affecting the sensitivity to lateral and vertical variations, as well as the depth of investigation. In this study, the Wenner–Schlumberger configuration was selected because it minimises distortion from subsurface bodies and provides high-quality data. Current is applied through the outer electrodes, while the inner electrodes measure the potential difference.

Field measurements were conducted primarily with a Syscal Pro 72 system using 5 m electrode spacing. This setup allows the acquisition of profiles up to 355 m long, reaching depths of approximately 65 m. Using the roll-along technique, longer profiles can be constructed by concatenating successive 90 m segments. Data processing was performed with Res2DInv (AGS Aarhrus GeoSoftware) using finite element inversion, a refined trapezoidal mesh with 4 nodes per cell, and a robust inversion algorithm to obtain reliable resistivity models of the subsurface.

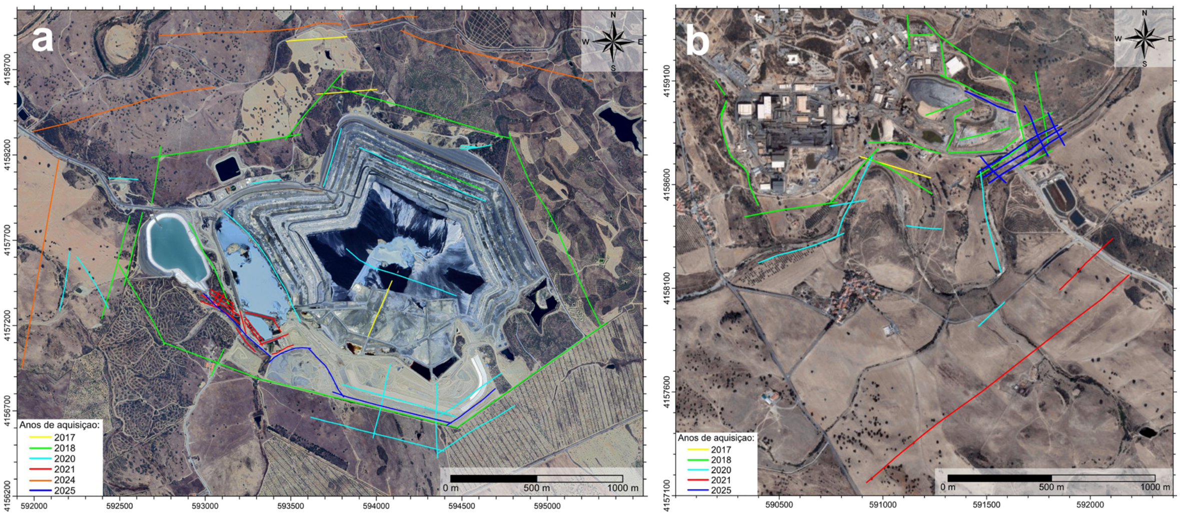
4 Results and discussion

The application of geophysics for environmental monitoring at the Neves-Corvo mine began in 2017 with a small pilot campaign aimed at testing the usefulness of ERT in that hydrogeological context and defining optimal acquisition and processing parameters. Since then, geophysical monitoring has become an integral part of the mine's environmental management strategy.

By 2025, a total of 41,270 m of ERT profiles had been acquired, strategically distributed to address multiple objectives (Figure 1). Over the years, new goals and increasingly complex challenges have emerged, reflecting both the evolving requirements of hydrogeological control and the progressive expansion of the monitoring network.

In the following sections, we present the different stages of this geophysical program, highlighting methodological developments, key findings, and the insights gained regarding groundwater flow detection, seepage identification, and sustainable tailings management. We also outline the next steps planned to further strengthen monitoring and environmental protection at Cerro do Lobo.

During the first acquisition campaigns, a standard resistivity scale was defined and systematically applied to all profiles in order to represent the main geological formations, subsurface features and the presence of conductive or natural fresh waters in the study area (Figure 1). While this scale provides a consistent reference framework for the majority of profiles, individual sections often reveal specific variations that require careful interpretation. These include the geological context of each profile, the position and orientation of fractures, as well as the size, morphology, and continuity of anomalous conductive zones. Figure 2 is an example of such a profile.



(a) (b)

Figure 1 Distribution of electrical resistivity tomography profiles by years in the (a) Cerro do Lobo tailings storage facility and (b) in the industrial zone

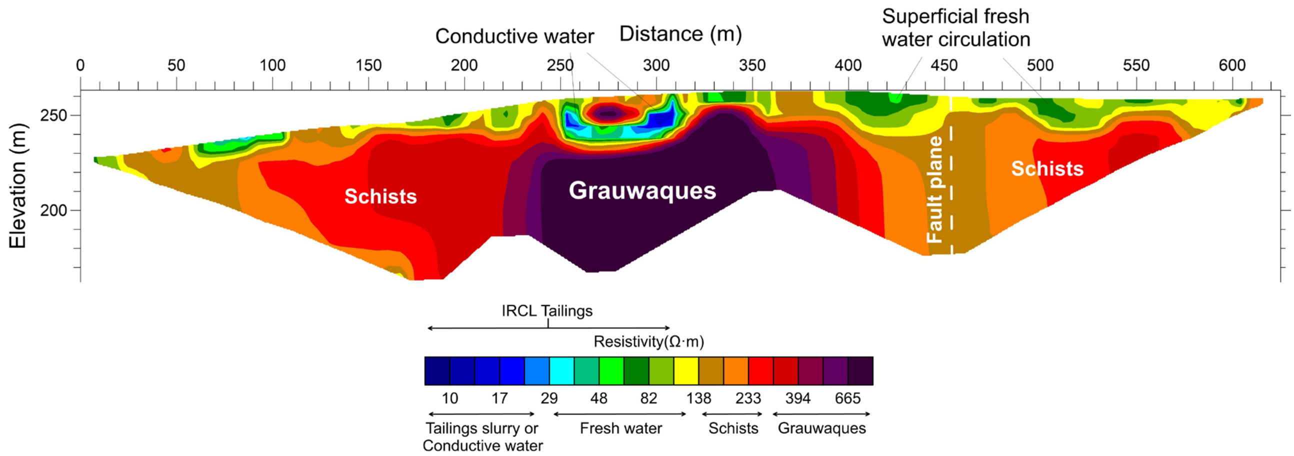


Figure 2 Example of an electrical resistivity tomography profile encompassing the main geological features of the study area and the presence of conductive or natural fresh waters. The colour scale has been adapted to represent the local geological settings

4.1 The enveloping approach

At the Neves-Corvo mine, two areas were identified for hydrogeological assessment: the industrial zone, where ore is extracted and processed, and the Cerro do Lobo TSF, where tailings and waste rocks are deposited. An initial reconnaissance survey was designed to detect potential escape pathways for conductive water, focusing primarily on the superficial system, i.e. the phreatic aquifer, where hydraulic conductivity is concentrated along fractures, faults and weathered zones. Although detailed tectonic and geological maps exist for the area, prior observations were limited to surface data.

The geophysical survey in this first stage had 2 main objectives: locate current acidic water leaks and identify previously uncharted faults that could act as future seepage pathways. Once the 2 main areas of hydrogeological interest were delineated, the enveloping approach was applied. This involved surrounding each hotspot with ERT profiles to pinpoint specific pathways of groundwater movement. Profiles were placed at a safe distance from the TSF to avoid direct influence from the tailings deposits, yet close enough to capture subsurface features connected to the source.

This approach provided highly informative and conclusive results, with distinct patterns observed for each area, enabling a targeted focus for subsequent hydrogeological investigation and mitigation measures.

4.1.1 Zona industrial

The enveloping survey around the industrial area was designed to cover its western, southern, and eastern flanks, coinciding with the zones of highest mining activity and aligned with the general groundwater flow direction towards the Ribeira de Oeiras.

In broad terms, the ERT results did not reveal significant patterns of deep conductive water migrating outward from the industrial zone (Figure 3). Instead, only minor shallow infiltrations were detected, which were subsequently identified, reported, and mitigated.

In addition, the survey highlighted a localised conductive anomaly corresponding to an old waste rock pile. While not directly connected to the current ore processing facilities, this feature represents a potential zone of increased groundwater conductivity and was therefore flagged for additional monitoring to assess its environmental impact.

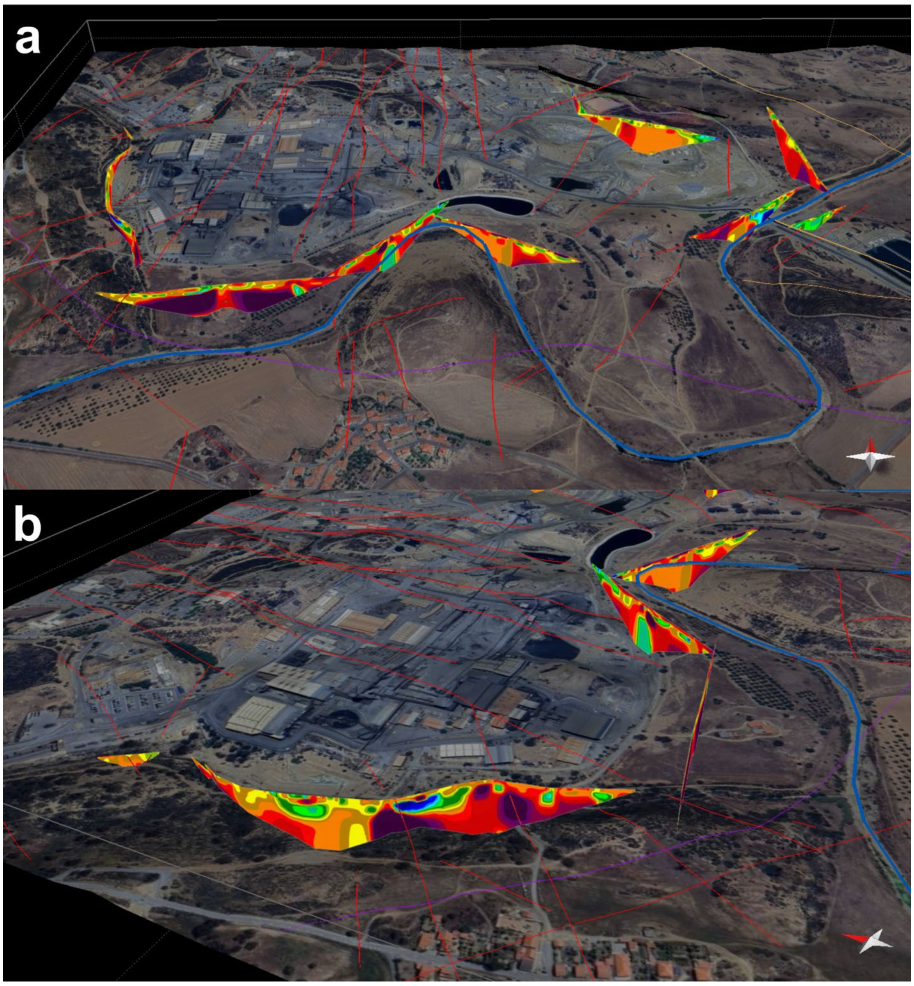


Figure 3 Distribution of electrical resistivity tomography profiles following the industrial zone enveloping approach, displayed over an orthophoto with the main tectonic structures highlighted in red and Ribeira de Oeiras highlighted in blue. (a) Perspective view looking north, (b) perspective view looking northeast

4.1.2 The Cerro do Lobo tailings storage facility

At the Cerro do Lobo TSF, the enveloping approach was applied by deploying ERT profiles around the entire perimeter of the deposit in all directions, with the objective of detecting potential seepage points regardless of their orientation (Figure 4). The general groundwater flow at the site is directed from north to south, making this the most likely pathway for possible leakage.

The results confirmed an absence of acidic or conductive seepage along the northern arc. However, these profiles provided valuable structural information, clearly delineating both mapped and previously unmapped faults that act as preferential groundwater pathways. In contrast, within the southern and western arcs, several conductive anomalies were identified that correspond to preferential flow paths of mine-influenced groundwater. These anomalies were subsequently prioritised for further hydrogeological assessment and monitoring.

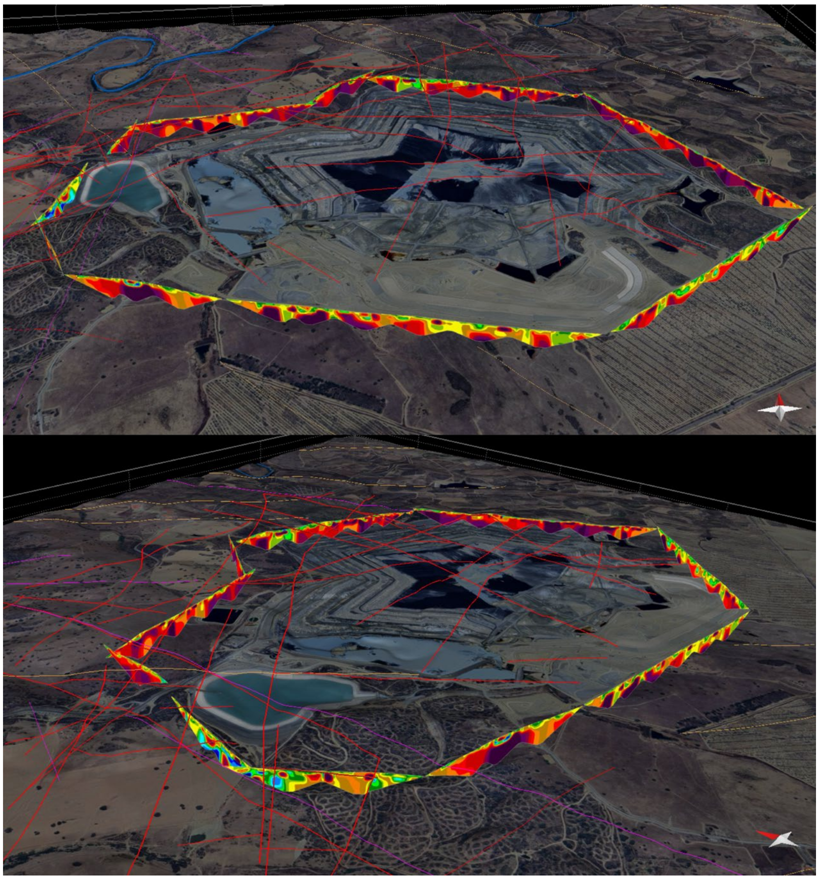


Figure 4 Enveloping approach of the Cerro do Lobo tailings storage facility, showing the distribution of electrical resistivity tomography profiles over an orthophoto and the main tectonic structures marked with red and purple lines

4.2 Mapping of preferential flow paths

Following the enveloping stage, the main seepage points associated with major fracture zones were identified. These conductive groundwater pathways were subsequently investigated in detail using additional ERT profiles arranged to track the potential escape routes.

In the industrial zone, 2 areas of possible conductive groundwater flow towards the Ribeira de Oeiras (stream) were detected (Figure 5, shown in blue tones). On the western side, a conductive body associated with a fault was initially identified; however, it showed no continuity to the south. Similarly, the deep conductive bodies detected along the eastern perimeter remained confined to their location without lateral propagation.

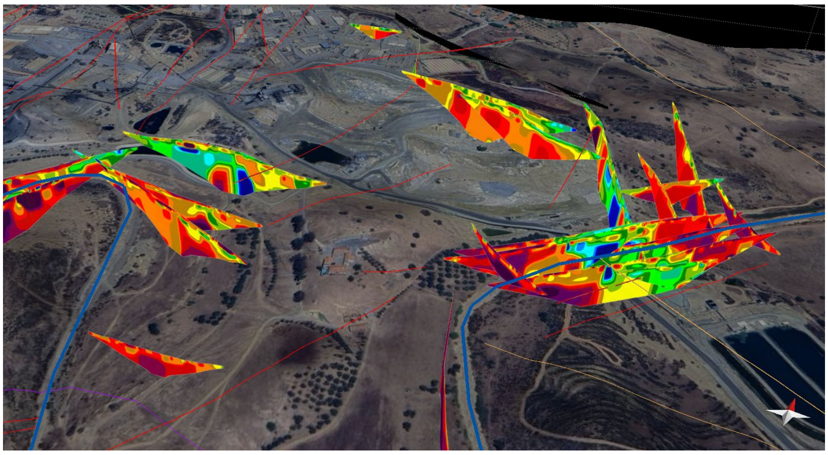


Figure 5 Results of the mapping stage in the industrial zone

In the Cerro do Lobo TSF, the enveloping profiles highlighted a potential preferential seepage pathway extending towards the west-southwest. To assess this anomaly, a series of perpendicular profiles was deployed to follow its continuity. It is important to note that not all conductive anomalies necessarily correspond to conductive water leakage (Figure 6); some deep conductive bodies may instead reflect the presence of black shales with disseminated pyrite and graphite. Nonetheless, several shallow conductive bodies were detected and interpreted as active pathways of conductive groundwater. These anomalies display clear continuity and can be traced outward from the enveloping survey of the IRCL towards the west-southwest, providing direct evidence of preferential seepage.

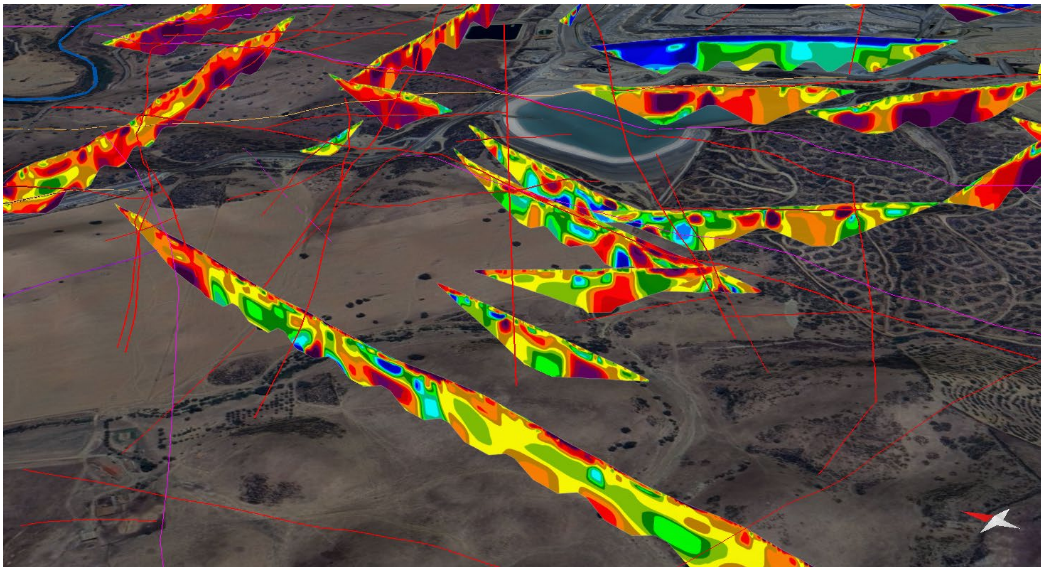


Figure 6 Results of mapping stage at Cerro do Lobo tailings storage facility (TSF). Preferential seepage can be observed following the blue tones from the TSF towards the west–southwest

4.3 Hydrogeological mitigation measures and monitoring

Long before the introduction of geophysical methods, the Neves-Corvo mine had already established a robust groundwater control system around the Cerro do Lobo TSF. Since the 1990s, Somincor progressively developed a dense network of interceptor boreholes for recovery (IBRs) and drainage wells designed to capture and pump seepage water back into the IRCL (Abreu 2025). This system evolved from just 7 IBRs in 1994 to its current configuration of 30 IBRs, demonstrating a long-standing commitment to environmental and groundwater management.

The introduction of ERT substantially strengthened this pre-existing strategy by providing high-resolution subsurface imaging that could pinpoint preferential seepage pathways with a precision unattainable by conventional methods alone. The low-resistivity anomalies detected in geophysical surveys guided the strategic placement of new piezometers at key locations.

The true synergy of this integrated approach was realised through hydrogeochemical analysis of water samples from these new wells. The results provided definitive validation of the geophysical interpretations: the water within these structurally controlled pathways exhibited a distinct calcium-sulphate ($Ca\text{-}SO_4$) facies, the characteristic signature of mine-influenced water. This allowed it to be clearly distinguished from the natural $Ca\text{-}HCO_3$ and Na-Cl groundwater facies of the area. By integrating ERT to locate potential pathways and using hydrogeochemistry to confirm their nature, Somincor not only validated the efficiency of its mitigation network but also transformed its monitoring capacity into a highly targeted, proactive, and scientifically robust system.

4.4 Environmental management best practices in mining

The work developed at the Neves-Corvo mine establishes a precedent for environmental management that can be exported to other mining operations, particularly those situated in complex, hard rock geological settings. Historically, mine remediation has relied on conventional hydrogeological techniques, such as surface observations and borehole data, which are often limited as they provide only point-source information without offering a complete picture of the subsurface dynamics. This limitation is especially critical in environments like the IPB, where groundwater movement does not occur as a diffuse plume through a porous medium but is instead structurally controlled by preferential flow paths along fractures, faults and thrusts within low-permeability schists and greywackes.

In this context, geophysical methods are an essential tool. ERT has proven to be particularly suitable, as it provides high-resolution images of subsurface resistivity contrasts that are directly related to the presence of conductive fluids, such as acid water. The methodological approach employed at Neves-Corvo is also a key factor in its success. The initial use of a perimeter screening approach, or an 'enveloping survey', proved highly effective as a reconnaissance tool, allowing for the rapid identification of potential leakage zones while ruling out areas that showed no evidence for impacts. Following this, subsequent ERT profiles, guided by the known tectonic framework, were used to confirm the continuity of these conductive pathways.

While the mine already had a robust mitigation system in place, including IBR pumps and a network of piezometers, the design of this system was based on traditional observations. The integration of geophysics has fundamentally enhanced this strategy, transitioning it from a reactive to a proactive and targeted system. This has not only allowed for the identification of previously unknown seepage conduits but has also been instrumental in verifying that existing mitigation measures are effective. This integrated methodology is now a core component of the long-term monitoring plan, used to assess remediated areas and proactively detect new potential issues as mining operations expand, thus setting a new standard for sustainable mine water management.

5 Conclusion

Based on the comprehensive study presented, the following main conclusions are drawn:

- Groundwater flow in the vicinity of the Cerro do Lobo TSF is demonstrated to be structurally controlled, with potential seepage pathways being governed by faults, fractures, and other tectonic features within the low-permeability bedrock. This confirms that migration of conductive waters does not occur as a diffuse plume but is instead channelled through a discrete network of preferential pathways.
- ERT has proven to be a highly effective, reliable, and low-cost non-invasive tool for characterising this complex hydrogeological environment. The phased methodological approach, beginning with a reconnaissance-level 'enveloping survey' followed by detailed mapping of identified anomalies, represents a robust and efficient strategy for delineating these preferential flow paths.
- The key success of the environmental monitoring strategy lies in the synergistic integration of geophysics with traditional hydrogeology. The ERT results have successfully guided the strategic placement of new piezometers, which in turn have validated the geophysical interpretations through direct hydrochemical analysis. This has optimised the monitoring network, increasing its efficiency and reliability for early detection at lower cost.
- The integrated approach implemented at Neves-Corvo serves as a best-practice model for the sustainable management of unlined tailings facilities in fractured, hard rock settings. It enables a shift from reactive, point-based monitoring to a proactive and targeted strategy, significantly enhancing environmental protection and providing critical, data-driven support for long-term mine closure planning.

Acknowledgement

This paper was supported by Somincor–Sociedade Mineira de Neves-Corvo through 6 projects for geophysical acquisition. In addition, the paper was supported by the project Caresoil–Caracterización y Remediación de la Contaminación de Suelos y Aguas Subterráneas en la era de la Transición Ecológica y Digital (CARESOIL-CM, TEC-2024/ECO-69).

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